The Use of Thermo-Mechanical Simulation in the Laboratory Classroom Environment

Daniel W. Walsh, Ph. D., and David Gibbs
College of Engineering,
California Polytechnic State University, San Luis Obispo

Abstract

It can be particularly difficult to provide students with meaningful laboratory exposures to kinetic and thermodynamic phenomena in solid-state materials in the context of a single quarter or semester course. This paper describes the development and use of a thermo-mechanical simulation device, and its use in a laboratory experience to improve undergraduate students understanding of complex thermodynamic and kinetic issues in a timely fashion. Laboratory procedure for the experiment is described in detail.

The laboratory allows students to observe, directly and synchronously, changes in the structure and mechanical properties of materials as a function of temperature, load and strain rate. Students are able to observe materials in the dynamic and non-equilibrium environments encountered in actual service and processing conditions, rather than in the equilibrium or otherwise artificial contexts discussed in the classroom or specially created in the laboratory. The paper discusses the exceptionally positive impact that this immediacy has an on student learning.

The laboratory discussed presents theory and application in a linked fashion. They are presented at a crucial stage in student development, kindling latent interest in some students and fanning smoldering interest in others. The course underpins deeper student exploration and provides an excellent segue to a number of other courses.

I. Introduction

Laboratories are a particularly expensive form of education; they are also a particularly potent vehicle for student learning. As professors, we must continually strive to insure that the return students receive from these potent vehicles warrants their expense, *and we must be able to demonstrate this benefit to any who question it*. Applied researchers go to the laboratory to wrestle answers from an impassive world, their intent is to detect, to appraise, and, eventually, to improve. We should send our students to the instructional laboratory to accomplish these same things. These goals must be established in the learning objectives for the laboratory. Instructional laboratories are our opportunity to pander to many different learning styles. They are our opportunity to emphasize the “learn by doing” credo, opening another venue to the intellect.

They provide a connection to the physical and practical for students often steeped in the academic and theoretical. They provide an opportunity for students to overcome the many “gremlins” lurking in problem resolution. They demonstrate the fuzzy edges and the abrupt transitions that characterize the disjoint and discontinuous real in contrast to neat abstract world described in precise mathematics. They provide an opportunity for inherently egotistical, individualistic, nascent entrepreneurs to learn the value of teamwork, as well as to develop communication and reporting skills crucial to professional growth. In short, laboratories provide a connection to enjoyable, hands-on activities similar to the challenging activities of professional life. They provide an opportunity for genuine discovery experiences of the sort that light intellectual fires which can burn for decades. Laboratories are activity based engineering education at its best, project-oriented efforts that immerse students in meaningful tasks. Laboratories provide the tolerance for ambiguity and contradictions that lead to the development of engineering judgment.

Laboratory productivity is tied to group attainment, which does depend on individual responsibility. The laboratory project should be too big for any individual to complete. The instructor must develop an open learning environment, promote interdependence and foster individual responsibility. As instructors, we can take a lesson from corporate America – rewards available to each lab group are based on group outcomes, individual rewards to group members are based on a collective assessment of each member by the instructor and by the group.

II. Desired Outcomes / Laboratory Objectives

Background

In accordance with ABET outcomes oriented assessment, laboratory objectives are shared with students at the beginning of each laboratory, as are the instructor’s desired outcomes. The course objectives are measurable goals that indicate how well the instructor’s laboratory outcomes are achieved.

Benjamin Bloom (Bloom, B., and 1956 *Taxonomy of Educational Objectives: Handbook I, Cognitive Domain*. New York; Toronto: Longmans, Green.) created a taxonomy for categorizing the level of abstraction in, (and therefore the depth of knowledge required to answer), questions that commonly occur in educational settings. The taxonomy was meant to provide a useful structure in which to categorize test questions, since professors will characteristically ask questions within particular levels. Bloom listed six levels in his taxonomy. *Each laboratory* should exercise all of these cognitive levels. *Each student’s* personal interaction with equipment/tools will lead to the accumulation of knowledge and skills required in the practice-oriented engineering profession.

Bloom’s first level was **knowledge**, which involved observation and recall of information, knowledge of facts, and knowledge of major ideas. Activities to measure outcomes desired at this level involve listing, defining, describing, identifying, labeling, and quoting. The second level is **comprehension** which involves understanding information, grasping meaning, translating knowledge into new context, interpreting facts, inferring causes, and predicting consequences. Activities to measure outcomes desired at this level involve summarizing, contrasting, predicting and estimating, differentiating and extending. The third level is **application,** which involves using information, methods, concepts and theories in new situations, and solving problems using required skills or knowledge. Activities to measure outcomes desired at this level involve demonstrating points, calculating solutions, and solving challenges. The forth level is **analysis,** which involves, seeing patterns, organizing parts and identifying components. Activities to measure outcomes desired at this level involve analyzing, separating and classifying. The fifth level is **synthesis,** which involves, using old ideas to create new ones, generalizing from given facts, relating knowledge from several areas and drawing conclusions. Activities to measure outcomes desired at this level involve combining information, integrating concepts, planning additional experiments, formulating hypothesis, and generalizing based on experience. The sixth level is **evaluation,** which involves comparing and discriminating between ideas, assessing the value of theories, reasoned argumentation and verifying value of evidence. Activities to measure outcomes desired at this level involve assessing, ranking, recommending, convincing, judging, explaining and concluding.

The Instructor's Desired Outcomes

Many outcomes are universally associated with laboratories, and differ only in context. However, four key outcomes, specific to this laboratory exist.

In many engineering and science courses, engineers are often instructed through convenient abstractions. They are often asked to treat materials as homogeneous isotropic continua (HIC). Though faculty warn students that this is an abstraction, and that more detailed analysis is required, the warning is often ignored. Students begin to accept the concept of a HIC, as it meshes with their macroscopic view of nature, and their monolithic view of materials. Students must be reminded that the concept of HIC is a terrible and an insidious lie. In fact, homogeneous isotropic continuum is probably one of the three most dangerous verbal triplets in the English language. Only two others have caused more problems, the second problematic triplet is "internal revenue service". The most dangerous triplet has been celebrated in myth, legend and literature, it is, of course, "I love you". Materials are inherently heterogeneous, universally anisotropic and patently discontinuous. The behavior of materials in engineering applications can be understood only if this is appreciated. **The first outcome specific to this laboratory is that the students will appreciate the heterogeneous, anisotropic and discontinuous nature of materials, and profound impact these features have on material behavior.**

Furthermore, students are often educated using the concept of thermodynamic equilibrium. In the context of materials engineering, this is nowhere more evident than in the ubiquitous equilibrium diagram, and the early pedagogical reliance on equilibrium concepts. Subsequently students are introduced to kinetics. Students need to be continually and forcefully reminded that there are no true-equilibrium situations. **The second outcome specific to this laboratory is that the students will appreciate the interrelationship between thermodynamic data and kinetic data, and understand the powerful concept of interfacial equilibrium.**

A third outcome specific to this laboratory is that students will appreciate physical simulation. Physical simulation of materials processing or use involves the exact reproduction of the thermal and mechanical processes in the laboratory that the material is subjected to in the actual fabrication or end use. A small sample of the actual material is used in the simulation. The material follows the same thermal and mechanical profile that it would in the full-scale fabrication process or end use of the material. Depending on the capability of the machine performing the simulation, the results can be extremely useful. When the simulation is accurate, the results can be readily transferred from the laboratory to the full size production process.

A final outcome, specific to this laboratory, is that students will learn how to use the Gleeble simulator, and extrapolate to other potential uses for the test system. Students will understand the relationships between specimen diameter, free span, constitution, and peak temperature and thermal distribution in the sample. Students will appreciate the difference between electric resistance and inductance heating

Laboratory Learning Objectives

By completing this laboratory participating students will demonstrate an ability to: 1. Apply the Gleeble simulator, quantitative microscopy and optical microscopy to make measurements of physical quantities, including testing and debugging an experimental system. 2. Devise an experimental approach, specify appropriate equipment and a set of procedures and implement those procedures. 3. Demonstrate the ability to collect, analyze, interpret data, and form and support conclusions. Make order of magnitude judgments about data correctness. 4. Identify the limitations of theoretical models as predictors of real world behaviors. Be able to evaluate whether theory adequately describes a physical event and establish and/or validate a relationship between data and underlying physical principles. Integrate thermodynamic and kinetic data. 5. Recognize unsuccessful outcomes and faulty construction or design, and modify the experimental approach accordingly. 6. Demonstrate appropriate levels of independent thought, creativity, and capability in problem solving in the real world. 7. Demonstrate competence in selection, modification, and operation of appropriate engineering tools and resources. 8. Recognize health, safety, and environmental issues related to technological processes and activities and deal with them responsibly. 9. Communicate effectively with a specific audience, both orally and in writing, ranging from executive summaries to comprehensive technical reports. 10. Demonstrate the ability to work in teams, including structuring individual and joint accountability, assigning roles and responsibilities, partitioning work, monitoring progress, meeting deliverable deadlines, and effectively integrating individual contributions into a final deliverable.

III. Theory

Constitutional Liquation

Savage (Weld Journal, 46: 411s, 1967) proposed a mechanism called "constitutional liquation" for the formation of grain boundary films at temperatures significantly below the bulk solidus of an alloy. Figure 1 is a portion of a hypothetical constitutional diagram for an alloy system exhibiting the behavior necessary for constitutional liquation. A_xB_y, is a second-phase precipitate, typically an alloy carbide or sulfide inclusion, distributed in the α solid solution matrix phase. When the alloy of composition C_o is heated relatively slowly, the solubility of B in the α matrix increases until the solvus temperature, T_2, is reached. Then, the last remaining A_xB_y should disappear, and the alloy is converted to a homogeneous single-phase solid solution of composition C_o. However, when the alloy is heated up rapidly, the precipitate A_xB_y does not have enough time to dissolve and thus still remains in the a matrix, even though it is above the solvus temperature, such as temperature T_3. Upon heating to the eutectic temperature Te, the liquid phase of eutectic composition e begins to form at the interface between A_xB_y and the α matrix. Further heating to temperature T_4 allows for additional dissolution of A_xB_y and formation of the liquid phase. At this temperature each remaining particle of A_xB_y will be completely surrounded by a liquid film of variable composition ranging from f at the A_xB_y interface to d at the interface with the α matrix. Thus, localized melting can be observed in materials at temperatures far below that required under equilibrium conditions, the equilibrium solidus temperature Ts. The material is heated too rapidly for the particle to completely dissolve, or for the solute to diffuse away. This produces, small, insular regions of eutectic composition – comprised of the particle and immediate matrix, separated from each other by a region of matrix material of composition O. When the eutectic temperature is reached, the material in those local regions melts. Subsequently, driven by surface tension differences, this liquid moves down intersecting grain boundaries.

Virtually each liquid pool created will intersect a grain boundary. At elevated temperatures, grains will grow until they intersect a precipitate particle. Once coated these grain boundaries are pinned owing to the wetting action of the films. No further grain growth would be expected until either the solute-rich liquid phase was dissipated by diffusion of solute or the local temperature decreased to below the effective solidus of the solute-rich liquid. If insufficient time were available to dissipate the liquid grain boundary films before the local temperature decreased to below the effective solidus of the liquid, grain growth would resume, leaving behind a solute-rich "ghost" grain boundary network.

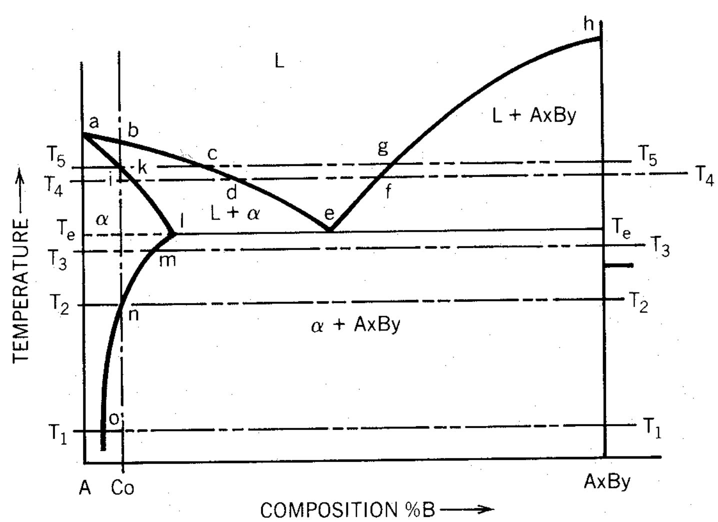

Figure 1, after Savage.

III. Materials

For this experiment, each student group will be provided with 10 samples of Aluminum Alloy 2024. The material is provided as 5” long, 0.25” round bar, with 0.5” lengths threaded ¼-20 on each end. This material is selected because it is easy to procure, easy to machine and is essentially a binary alloy of aluminum and copper. In the range of the nominal alloy composition, it is subject to classical constitutional liquation.

IV. Equipment and Procedure

The Gleeble Simulator

The Gleeble is a fully computer interfaced device capable of simulating any thermal and/or mechanical history experienced by a material. The device employs a low frequency (60 cycle) alternating current to heat a specimen by resistance (impedance). The specimen is actually the secondary of a transformer in which the voltage is stepped down from 480V to 10V. The device switches 0.25 MW, so very high currents can pass through the sample. Specimen geometry is arbitrary, but is typically round bar or flat bar. Cross sections can be as great as 625 square mm, and heated lengths can be over 400mm. Specimen temperature is controlled by either thermocouples mounted directly to the sample or by an optical pyrometer. Pyrometer control is required for experiments involving carbon/carbon composites. The device can heat/cool at controlled rates from 10,000 C per second to 1 C per hour. Jaws that provide electrical contact grip the specimen. These jaws form the bed of a hydraulic mechanical test apparatus. Mechanical control is provided by any one of several modes; force, stroke, dilation. Thus the Gleeble allows the experimenter to control temperature and one mechanical variable while recording up to eight other signals. A transient data recorder incorporated into the control system gathers information. The Gleeble has been developed with both mechanical and thermal simulation capabilities; neither capability was developed in a secondary manner. The Gleeble is unique among simulators in that it performs thermal and mechanical tests equally well.

The equipment allows the study and test of materials in the same dynamic fashion they are fabricated and used. **The application of the Gleeble to any materials laboratory course is limited only by the experience, imagination and, occasionally, the courage of the user.**

In this experiment, students are not told that they will be studying the effects of constitutional liquation! Students are asked to design a test matrix to examine the microstructure and the mechanical properties of the Al 2024, as a function of peak temperature and heating rate. Samples are heated to a specific temperature, and pulled to failure. Students measure loads at failure, and the sample ductility. The instructor provides enough guidance so that at least one of the test temperatures selected is above the eutectic temperature for the alloy. Students are coaxed into selecting two different heating rates, one that will allow for particle dissolution and diffusion of solute without the formation of liquid, and another rapid enough to produce constitutional liquation. As part of the study, students characterize the microstructure of the material at room temperature, and at the series of test temperatures selected. Everything proceeds normally until the super-eutectic peak temperature, rapidly-heated sample is pulled. The unexpected result gets every ones attention, and starts to beg ethical questions. Groups typically feel that they should repeat the test; because the initial consensus is that there was some sort of procedural or material problem with that particular sample. At this point, the real voyage of discovery has begun.

V. Data / Analysis

Students analyze the microstructural data, and the mechanical properties they measured. The key point of discussion is typically the difference in microstructure, strain at failure and load at failure in the samples tested at the super-eutectic temperature. The rapidly heated sample exhibits markedly lower strength, and lower ductility. Several student groups detect evidence of unexpected melting in these samples. Students then begin to piece the important microstructural information from the other samples together. Eventually, they are able to reconstruct various approximations to the theory of constitutional liquation.

At this point groups are offered more samples to test the hypothesis they have developed. Each year at least one group makes the truly remarkable leap to adding a hold time to the rapidly heated sample. This allows the sample to "resolidify" at that fixed temperature, and produces a marked increase in strength and ductility. It also provides further proof for the mechanism proposed by the students.

VI. Reporting

Students are required to keep a laboratory logbook, listing work done and observations made on each lab day. The lab book is signed and dated by all group members. Each group is asked to prepare a detailed formal laboratory report describing the experiment, providing data, discussing results and offering conclusions and suggestions for further study. The report must contain a one-page executive summary. In their report, the students are also asked to evaluate the laboratory and asked to suggest improvements. In addition to the verbal communication inherent in daily laboratory operation, groups are also asked to report their findings orally. During the oral presentation groups are asked questions about other alloy systems, about the sensitivity to constitutional liquation for precipitates comprised of interstitial elements vis-à-vis those comprised of substitutional elements and other questions that provide the students with "intellectual runway" or room to grow.

VII. Evaluation

Students are evaluated by group and as individuals. Rewards (grades) are provided based on a corporate model. The instructor evaluates groups; rewards (points) available to each lab group are based on group outcomes, such as the quality of the report and presentation. The instructor bases individual rewards (grades) to group members on a collective assessment of each member by other members of the group; however, the total points available to the group delimit rewards.

VIII. Conclusion

Student experience with the laboratory has been very positive. Comments indicate that students are interested in the material and energized by it. The opportunity for genuine discovery, even though "engineered" into the laboratory, is considered a strong vehicle to help students develop true professionalism, even while cloistered in the academic setting.

DANIEL WALSH
Daniel Walsh is a Professor of Materials Engineering, program director of General Engineering and Associate Dean for College of Engineering at California Polytechnic State University, San Luis Obispo. He also serves as Director for the Advanced Technologies Laboratory. He received a B.S. degree in Biomedical Engineering from Rensselaer Polytechnic Institute in 1973 and a Ph.D. in Materials Engineering at Rensselaer Polytechnic Institute in 1984.